SUSTAINABILITY DRIVEN INTEGRATED PRODUCT DEVELOPMENT FOR HUMAN INTERFACE DEVICES: AN ANALYSIS OF INDUSTRY BEST PRACTICES

A SYNOPSIS

Submitted by

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1. INTRODUCTION

Product lifecycles have significantly decreased across various industries as a result of globalised marketplaces, technological innovation, and changing customer behaviour. Companies must optimise their operations in terms of productivity, time-to-market, and quality if they want to continue operating profitably and introduce profitable goods [1]. With an expanded range of products provided on the worldwide market the customer can be able to select their product based on their need [2]. The industries have needs to meet out the needs of domestic and international markets [3]. In order to compete in the global market the industries are needs to manufacture the products in the stipulated time based on that the industries can able to sustain in the market [4]. By understanding the product life cycle the company can able to realize when the product needs to launch and withdraw the product from the market, its position in the market in relation to rivals, as well as the accomplishment or failure of the product [5]. Accepting the sustainability as a science represents a major ontological shift in society. Sustainable development is the process of expansion to meet their current requirements and it's transformed into high valuable product without compromising the opportunity of future generations to meet their needs [6]. The requirement provides the characteristics like design, forms, features, through which new design can be embodied through engineering and manufacturing. Developing the new product is not only an easy task but also risky factor because the general victory rate of the new product is 60 percent [7]. Most of the firms are having the joint venture to develop the product which leads to reduce the risks associated with innovation but it's mostly failed [70 percent] in the market [8]. The imperative task of any organisation is to have a formal and appropriate procedure to guide the innovation process based on that the organization can able to successfully introduce into the market with reduction in cost and development time.

The Finite element method can be applied for all kinds of engineering fields to analysis the structure in the form of static or dynamic condition [9-10]. Computational Fluid Dynamics [CFD] has become a vital technology for engineers over the last few decades, as it allows them to make better predictions about the airflow around different engineering components. CFD is economically cheaper to analysis the aerodynamics characteristics especially in new aeroplane design. CFD is used to analyse the components like rotating blades of turbines, compressor in aircraft engines, the

combustion process in diesel engines and pressure drop in exhaust system. The governing equation based on three fundamental physical properties [11-12]

2. LITERATURE REVIEW

Product development is a creative activity that transforms a commercial opportunity and fresh technical research into useful items for the customers. Wang et al. [13] suggested the organisations to set up their product development procedures such that all of the primary departments are involved. Schoggl et al. [14] reported the early stages of product development, the CSPD permits qualitative evaluation of environmental, economic, and social issues while taking the complete life cycle into account. Thariq et al. [15] examined design parameters (dimensions) for fixed type side mounted desktop chairs to improve the comfort level and establishing a relationship between the desk's proportions to the chair's dimensions. The chair model was created by CATIA and the structural model analysis was carried out by the ANSYS software. The data consider for analysis the such as hip width for cushion width, buttock to popliteal length for thigh support, and sitting shoulder height for seat back lateral support and ANSYS software was used for the structural analyses to calculate the deformation and Von Mises Stress to obtain the optimum design. Based on the literatures the following research gaps were identified and the same reported in the next section.

3. RESEARCH GAP

Sustainability-driven Integrated Product Development for human interface devices is an emerging area of research that seeks to create products. There is a research gap in understanding how these practices can be integrated into the design and development of human interface devices.

- There is a need for research to analyze the industry's best practices in sustainability – driven integrated product development for human interface devices.
- Understanding the industry's best practices in this area could provide insights into how companies can improve their sustainability performance, reduce their environmental footprint, and enhance their brand image.

- It could also inform the development of guidelines and frameworks for sustainability-driven integrated product development, which could benefit companies across different industries.
- The research could also focus on the challenges and opportunities in adopting these practices and assessing the outcomes and impacts of sustainability-driven product development on the environment, society, and the economy.

4. OBJECTIVES

The objective of this research is to select three different products from the segments and analyze industry best practices for sustainability-driven integrated product development for human interface devices.

- To review the literature on sustainability – driven integrated product development for human interface devices.
- To identify the effective practices and analyze their impact on achieving sustainability goals to release the product on Time to Market. The research will also identify the challenges and barriers faced by the industry in implementing sustainable practices.
- The research aims to provide insights into the best practices used by the industry for sustainability - driven integrated product development for human interface devices.
- By analyzing the effectiveness of these practices, the study will provide guidance for the industry to develop sustainable products. Overall, the study will contribute to the development of sustainable products in the human interface device industry.

5. EXPERIMENTAL METHODOLOGY

5.1 Process Methodology

The process flow chart for the proposed research is given in the Figure 1. Three different products from different domains are selected for the detailed assessment. For each product, the process methodology adopted is different and they are based on the industrial demand. During the process evaluation, the product – life – cycle assessment is made to find a best analysis.

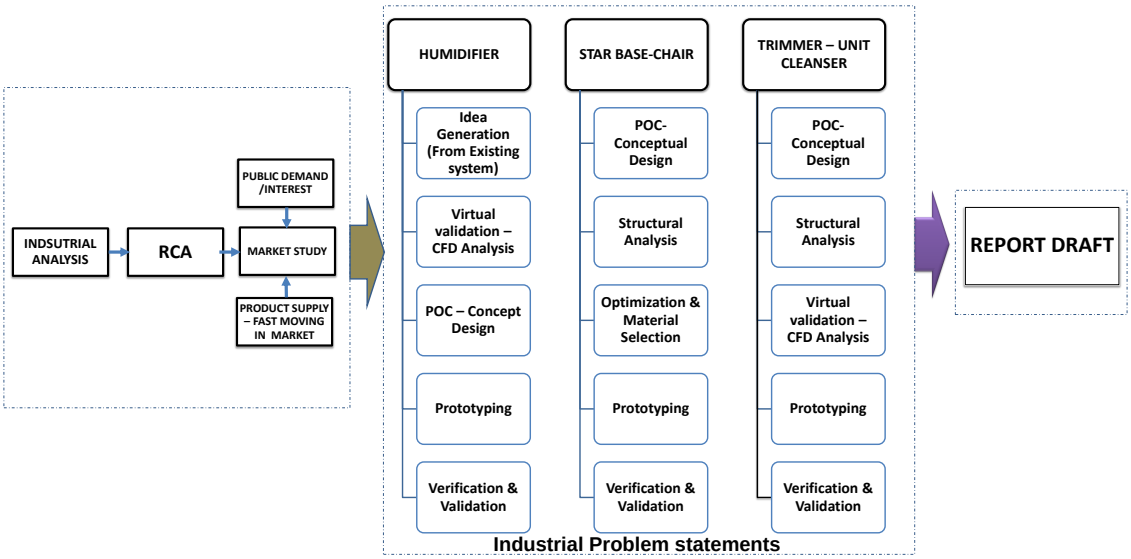


Figure 1: Process Flow chart for the proposed research

5.1.1 Design and development of air humidifier

A detailed study, conceptual design, analysis, and testing were done on the following areas to achieve the desired output Figure 2. First, the Design of Experiments (DoE) is done on the humidifier samples available in the market to open new possibilities. The process was initiated with a conceptual design of a humidification chamber based on the DoE.

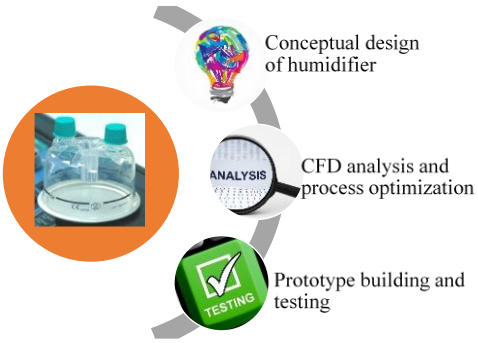


Figure 2: Design plan for investigation on humidifier system

Further, CFD-based analysis is adopted to optimize and improve the humidifier unit's airflow path. In addition, the humidifier performance, and critical parameters such as material type, airflow velocity, output operating temperature, and RH percentage based on the humidifier design (inlet and outlet path) are derived based on the analysis and multiple experiments results. The above experiments and analysis result in an optimized product development framework for the humidifier design. To design the humidifier

system, the working condition is retrieved and made standard from the existing system in the market.

5.1.2 Star Base Chair

PLM is the business activity of managing, in the most effective way, products of a company, all the way across their lifecycles from the very first idea for a product until it is retired and discontinued. Figure 3 shows the basic product life cycle chart. It is a strategy tool that helps companies plan for new product development and refine existing products as per the customer requirements. A product life cycle has four distinct stages, namely Market Introduction; Growth; Maturity; Saturation and decline stage. It can also be used to plot the progress of a product through its life span.

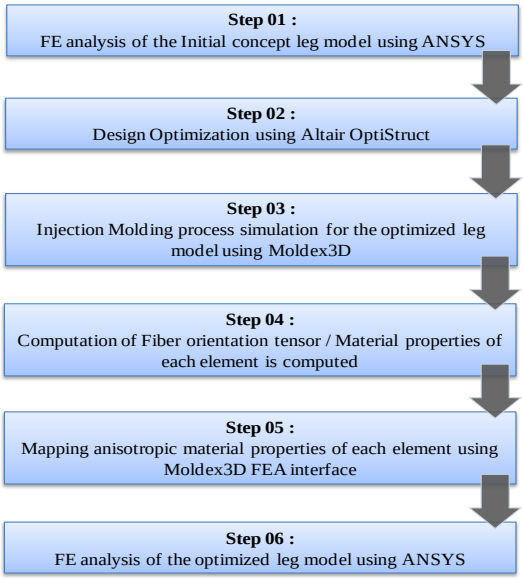

Step 01 :
FE analysis of the Initial concept leg model using ANSYS
Step 02 :
Design Optimization using Altair OptiStruct
Step 03 :
Injection Molding process simulation for the optimized leg model using Moldex3D
Step 04 :
Computation of Fiber orientation tensor / Material properties of each element is computed
Step 05 :
Mapping anisotropic material properties of each element using Moldex3D FEA interface
Step 06 :
FE analysis of the optimized leg model using ANSYS

Figure 3: Basic Graphs to illustrate on PLCM

5.1.3 Commercial hair trimmer cleaner unit

Figure 4 shows the stages engaged with item advancement of a unit cleaner. The task is launched with information assortment and the course of events is planned for the new item configuration is created according to the norm. In idea determination stage, the item plans are drafted/displayed utilizing various instruments; accordingly, scarcely any virtual testing is additionally proposed to complete. For this situation the business item accessible in the market are recognized to make a correlation study. The significant item in the market is Philips, Panasonic, Braun and other district made neighbourhood items.

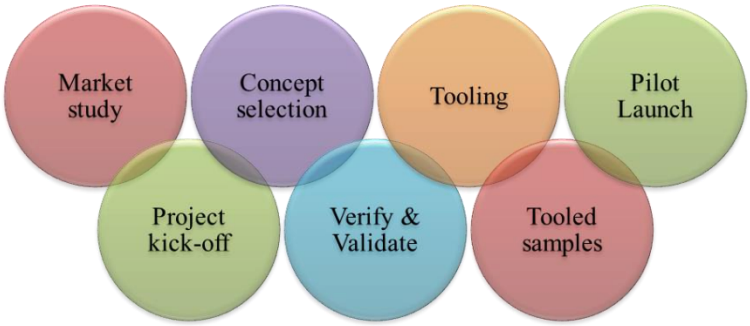


Figure 4: Stages involved to develop a unit cleaner product

5.2 Experimental Tools

The two different tooling concepts are adopted to handle the problem identified. One is to develop the product through conceptual thinking and data inference. Another one is to support the conceptual design through different computational process. Table 1 indicates the tools adopted for conceptual design and product development.

Table 1: Tools adopted to design and develop the product for industrial demand

Conceptual Design in Complex Product	Computational support in Product Development
➢ Product life cycle management ➢ PUGH matrix ➢ Data analysis	➢ NX CAD ➢ FEA - ANSYS ➢ Moldex3D ➢ StarCCM+ ➢ LS Dyna

At conceptual design stage, a comparison is made between the existing product and future product to be developed in design are evaluated. To perform the product concept valuation, the PUGH matrix has been made to compare and contrast the details available on existing product. As an initial point, fixing a product datum line for validation is an important task. In this research, the validation score is fixed in the range of -2 to +2 with tie line. Each and every product are verified and scored to identify the novelty in the product with respect to the different concept questions. The questionnaires to identify the product are assemble level, product quality, usability, product cost, aesthetics (finishing, colour and appearance), number of spare / parts and product

compactness. Response to the questionnaires with the score card arrived through PUGH matrix has been analysed to study the feasibility and challenges in modification of the product is identified. From the analysis it has been proposed to develop a separate cartridge unit with a detergent medium with the following features. Problem statement is that the current product in market is larger in size, extra efforts to operate, storage and better cleaning results. From every one of the plans, best ones are chosen and further defences will be conveyed following industrial demand or need analysis. Further it will be check and approved at each stages likely; the plan archives, details and so on are inspected for the following advancement. The end clients' requirements are met by practical testing and check of item. In tooling stage, the apparatuses for the creation are noted and customized for assembling the item. The tooled tests are delivered and tried. After which the item is brought to showcase for its application.

6. RESULT AND DISCUSSION

6.1 Sustainable design and development of the cleanser unit

For the System Cleanser, the prerequisites of an item and it audit are gathered from the market. The task is launched with information assortment and the course of events is planned for the new item configuration is created according to the norm.

Table 2: PUGH Matrix for the product existing in the online market

Product & factors	Product 1	Product 2	Product 3	Product 4
Assembly	0	-1	-1	-1
Manufacturability	0	0	1	0
Usability	0	0	0	0
Cost	0	-1	0	0
Aesthetic	0	1	0	2
Number of parts	0	-1	1	0
Compact design	0	0	0	0
Net score	**0**	**-2**	**1**	**1**
Rank	**0**	**4**	**2**	**2**
Continue	**No**	**NO**	**NO**	**NO**

In idea determination stage, the item plans are drafted/displayed utilizing various instruments; accordingly, scarcely any virtual testing is additionally proposed to complete. For this situation the business item accessible in the market are recognized to

make a correlation study. Table 2 indicates the study on cleanser unit through PUGH matrix. The arrangement of System Cleanser system was immersed in a liquid detergent (water + detergent) case at initial condition and pump actuating situation designed with Unigraphics NX modelling is shown in Figure 5. The direction the liquid flow from the cartridge to unit system will be varied in a different direction with respect to the case design. The level of liquid available in the cartridge is 27 mm. The level of liquid in the cartridge found pumped within 0.3 s and the same liquid starts to reach same cartridge with a second.

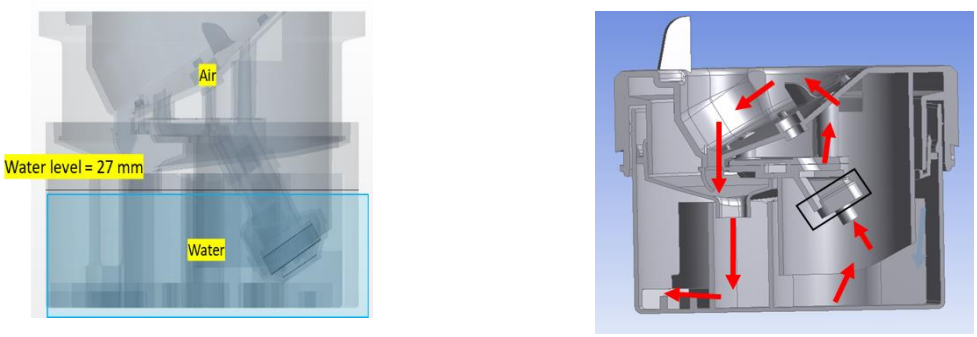
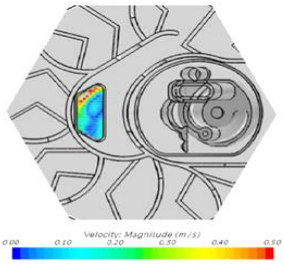


Figure 5: Design represents the arrangement of System Cleanser at initial condition and pump actuating situation

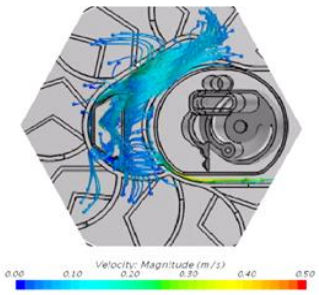
During the cleaning process, the pump is actuated to rotate at a speed of 2000 rpm to pump liquid from pump volute to washout region and back to cartridge. At a maximum velocity of detergent fluid is 1 m/s and maximum pump pressure of 1000 Pa. The amount of liquid from the cartridge will be pumped at a flow rate of 1.8g/s (that is 18 ml/s).The rotating pump has high efficiency to acquire entire liquid from the cartridge to pump and splash over wash out region. The maximum time required to complete one cyclic flow of the liquid is 3.8s. At the pump zone the maximum fluid velocity has been noticed and the turbulence increased at cartridge during pump suction at a maximum velocity of 1 m/s. At this regime, the maximum pressure is noticed at the pump rather than the other regimes. Fluid from the suction point found moving towards (air) wash zone at a uniform velocity. Maximum pressure generated at the suction of the fluid is 950 Pa and it is uniform throughout the pump. At pump discharge point, the pressure found decreased and it is in the range of 850 to 900 Pa, as the wash out zone is open to air. Flow of fluid from the pump to wash zone is in lamellar (parallel) flow and the level of fluid velocity found in the range of 0.8 m/s to 0.95 m/s. The distraction happens at the end of pump orifice and lift velocity found reduced. Subsequently, the turbulence has originated at air

zone due to high velocity of the fluid striking over the ridge. After a maximum turbulence at the wash zone, the function of the fluids completed and the same drains with respect to the gravity direction. To discuss in detail, the fluid flow direction on cartridge has been simulated for the alternate walls. The three – dimensional (3D) design of the cartridge having baffles with alternate openings in the case housing is given in Figure 6a.

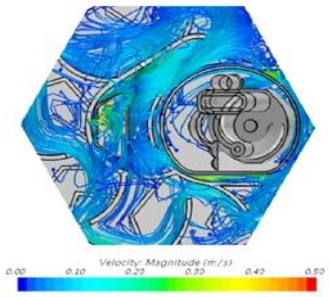
(a) 3D model of cartridge



(b) Initial condition of cartridge



(c) Flow at 1.0s



(d) Flow at 3.0s

Figure 6: (a-d) Fluid flow direction and pressure variation on cartridge at different time duration.

For the same simulating pressure and fluid velocity; the fluid flow direction and its magnitude are identified through fluid flow analysis. Figure 6b represents the initial position of fluid to pump out from the wash zone and cartridge. Initially, the pump starts to drive the fluid from cartridge and moves towards first housing as shown in Figure 6c. At the same thriving pressure, the fluid squeezes to baffle housing with same pressure and flow of fluid makes ballets towards the openings. At the second stage, the fluid flow at first opening and produces severe turbulence and leads to move toward the alternate openings in the baffle. Figure 6d, represent the turbulence and the maximum fluid pressure generated over each baffle. The rate of pressure found decreased from initial point to end of cartridge zone. To discuss in detail the 3D view of the simulation is reported for better understanding.

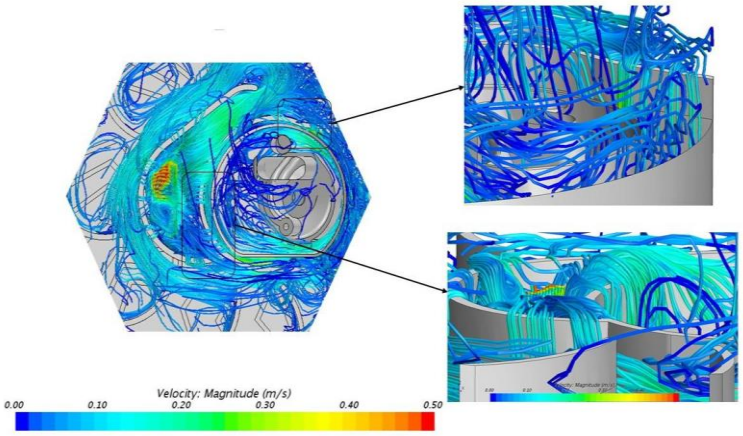


Figure 7: Fluid flow at baffle casing and openings indicating the flow velocity magnitude.

Figure 7 shows the flow of fluid in three dimensional with velocity magnitude. The fluid flow spills out of the cross wall and side ribs at varying velocity. The velocity magnitude found less while crossing the housing and it has weightage while crossing the baffle openings. It is also noticed that the magnitude turbulence of the fluid found less while crossing the baffles. The vortex / swirl of the fluid is due to multi corners at a close angle in the inner close wall. The velocity of the fluid vortex flow at the beginning (from the pump) is 1 m/s. At the same, the velocity found reduced due to atmospheric pressure and it found reduced with gravity flow

6.2 Design Optimization of Office Chair Star Base Leg using Product LCM

Since the star base is widely used in all industries, the cost of time & delivery is highlighted for its needs. Here, the needful design modifications are based on weight, cost, failure, time and aesthetics. The leg with perpendicular ribs of 3 mm and the wall thickness of 1.8mm. The improved results show reduction in 10% of stress rate when compared with the existing design. The leg with crisscross ribs at 45 degrees and with 3mm thickness and the wall thickness of 1.8mm. This results in reduction of stress rates comparing to the previous design. The wall thickness is modified as 3mm in this design experimentation. During analysis, the time duration for simulation processes of the previous test cases is less than this case. Since the thickness is changed, the base part wasn't aesthetically good. In addition to that, material usage will be more here; But, these two analyses displayed the reasonable decrease in the stress produced. The leg geometry is meshed using the SOLID186 in ANSYS. The element is defined by 20 nodes having

three degrees of freedom per node: translations in the nodal x, y, and z directions. Isotropic material properties are used during the initial stage evaluation of leg. The Material PA6 35% Glass Filled is used with a Young's Modulus of 12000MPA, poison's ratio 0.35, tensile strength 190 MPa, tensile Elongation 4% and flexural strength 260 MPa are used for analysis. Figure 8 shows the 3D modelling, meshing and load conditions applied for the chair case model. The cyclic symmetry condition is assigned at the cut locations. The region where the gas cylinder mounted is constrained in all the direction to avoid the rigid body motion. The force of 2224 N is applied to capture the bending and the torsion effect in the leg in separate load case. The BIFMA x5.1 office chair standard defines specific tests, the laboratory equipment that may be used, the conditions of tests, and the minimum acceptance levels to be used in evaluating general-purpose office chairs. This standard is intended to provide manufacturers, specifiers, and users with a common basis for evaluating the safety, durability, and structural adequacy of general-purpose office chairs. The Base test as per the standard is captured in the FEA.

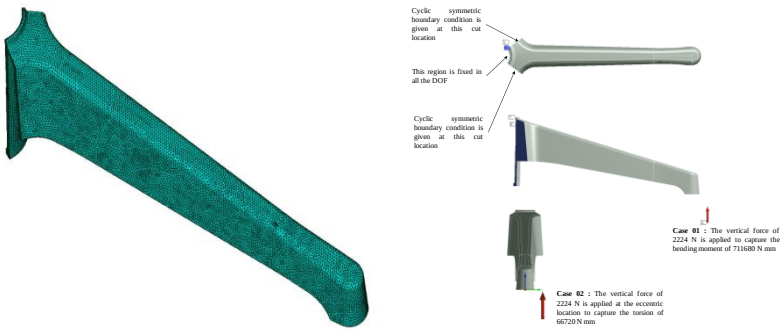

Cyclic symmetric boundary condition is given at this cut location
This region is fixed in all the DOF
Cyclic symmetric boundary condition is given at this cut location
Case 01 : The vertical force of 2224 N is applied to capture the bending moment of 711680 N mm
Case 02 : The vertical force of 2224 N is applied at the eccentric location to capture the torsion of 66720 N mm

Figure 8: 3D modelling with discretization and load boundary conditions of leg

Figure 8 shows the 3D modelling, meshing and load conditions applied for the chair case model. The cyclic symmetry condition is assigned at the cut locations. The region where the gas cylinder mounted is constrained in all the direction to avoid the rigid body motion. The force of 2224 N is applied to capture the bending and the torsion effect in the leg in separate load case. The BIFMA x5.1 office chair standard defines specific tests, the laboratory equipment that may be used, the conditions of tests, and the minimum acceptance levels to be used in evaluating general-purpose office chairs. This standard is intended to provide manufacturers, specifiers, and users with a common basis for

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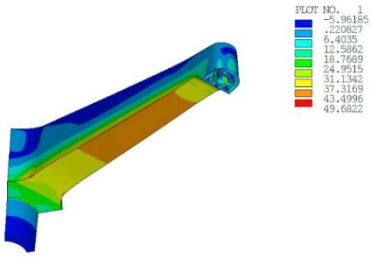
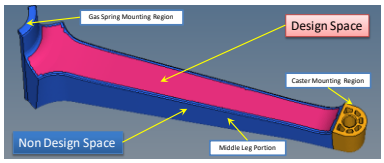
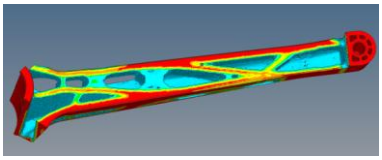


Stress Plot for initial leg model

Optimized leg CAD model



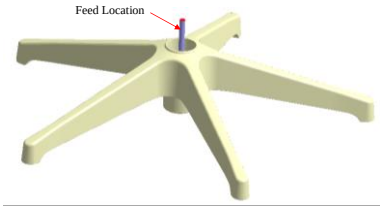
Topology Optimization Parameter



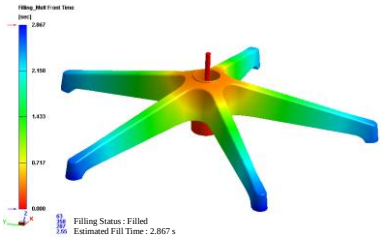
Topology Optimization Result

Figure 9: Stress plot and results of optimized model of the leg with constraints

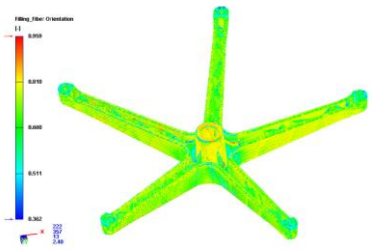
Figure 9 shows the stress plot and optimized model of the leg found over proposed design. Topology optimization gives the approximate rib pattern at the bottom of the leg, so to validate the optimization result, 3D CAD data need to be prepared. The initial IGES file is exported from the optimization result. The same is exported to design modular and final proper CAD model is generated. This model is taken to the Moldex3D software for the mold flow simulation. The anisotropic property induced due to the fiber orientation is mapped to the FEA mesh for the final validation. The induced process anisotropic property orientations are based on density. In Mold design, two-plate construction is designed for leg part and cold feed, ring gate design is suggested in center of the part. The gate thickness provided 60% of the nominal thickness. Ideal cooling is considered for this analysis (Uniform mold temperature). Analysis performed are fill, pack, cool &warp. The material is selected from Moldex3D database and material used is (Nylon) PA6-35% GF. On completion of the pre-process design & meshing, the part is taken for injection molding (Solver).



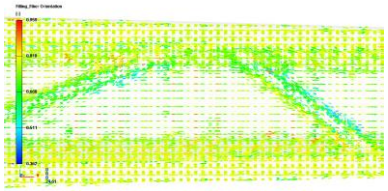
3D model of Injection moulding



Mould filling model



Fiber Orientation Plot



Fiber Orientation in the ribs

Figure 10: 3D model of Inject mold and fibre orientation of in the optimized leg case.

Table 4: Optimized results of the chair – Concept model and Optimized model

S.No.	Leg Model	Mass (kg)	Load Case	Displacement (mm)	Allowable displacement	Stress (MPa)	Allowable stress
1	Concept model	1.54	Case 01	6.8	15	49.68	190
			Case 02	5.87		40.69	
2	Optimized Model	1.31	Case 01	10.87		179.21	
			Case 02	9.45		145.04	

The part can be filled easily with center ring gate and estimated fill time required to fill the cavity is 2.867s for which filling pressure & temperature observed in the cavity is within the acceptable limit. Potential molding problems like weld & knit lines are observed as shown in Figure 10. Table 4 infers the optimized data extracted from the FEA model. The magnitude of the displacement is less than the allowable displacement of 15 mm and the maximum stress is less than the allowable limit of 190 MPa. Henceforth, the design is safe.

6.3 Design, development and manufacturing of air humidifier

The design was made such that the humidifier chamber complied with the ISO 8185 standards. As per the standard, Humidifiers can be used with patients whose upper airways have been bypassed by a tracheostomy or tracheal tube. The upper airway provides 75% of the heat and moisture supplied to the alveoli. When the upper airways are bypassed, the humidifier needs to supply this missing heat and moisture. Since the total required moisture input is 44 mg/l, the portion supplied by the humidifier is 0.75 x 44 mg/l = 33 mg/l. In this case, the water level has been taken for maximum (130 ml) and minimum level (30 ml) in the humidifier reservoir (barrel) with two different ranges of inlet airflow for investigation. The dynamics of the air medium concerning the simulating environment were found drastically flooded throughout the reservoir chamber internally. The flow of air inside the humidifier chamber is as shown in Figure 11 (a-d).

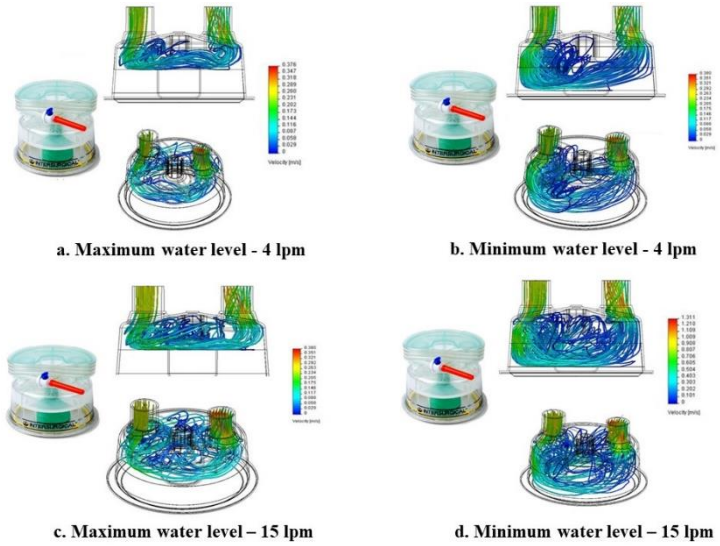


Figure 11: (a-d) Design, analysis and process optimization stages for humidifier

From the analysis, it is clear that the flow of air inside the reservoir is less, and the same has been forced out in the maximum water level humidifier unit. This situation conflicts with the minimum water level. Based on the input air flow rate, the compressibility of the air found increased inside the reservoir. Due to compression (airflow region – empty volume) inside the reservoir, the pressure increase in the airflow has increased tremandously and subsequently influenced outlet velocity. The air's outlet velocity from the humidifier is recorded for the first case with different work conditions. The air velocity is found that the outlet velocity is four times substantial for maximum

water level as 1.32 m/s compared to the minimum water level 0.377 m/s. There are no significant changes in maximum and minimum water levels for the inlet air flow rate. The velocity of the air drastically increased owing to turbulence and fluidic behaviour inside the humidifier. Further the concept design has been increased with more ideas on development.

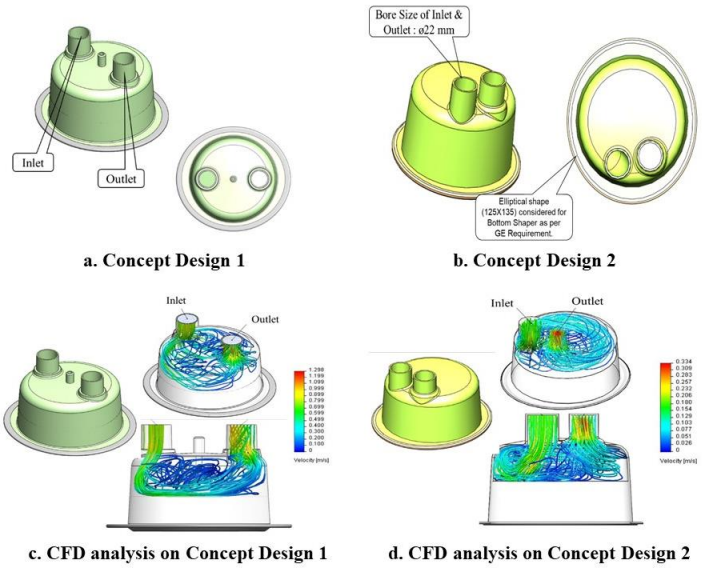

Inlet
Outlet
a. Concept Design 1
Bore Size of Inlet & Outlet : ø22 mm
Elliptical shape (125X135) considered for Bottom Shaper as per GE Requirement.
b. Concept Design 2
Inlet
Outlet
c. CFD analysis on Concept Design 1
Inlet
Outlet
d. CFD analysis on Concept Design 2

Figure 12: (a-d) Sustainable design and development for air humidifing unit

Figure 12a and 12b, illustrates the new model proposed in the sustainable design of the air humidifier unit. Sealing design is a crucial parameter on the humidifier assembly. It has an elliptical structure with self-locking material over the chamber. It needs to ensure to withstand the temperature with 0% leakage. The sealing cap design may enrich the whole unit to maintain better performance with increased air outlet velocity and pressure. The top covers are easy to unlock and disposal / replaceable for multiple usages. The fluid dynamic analysis has been performed with the same working environment and process condition using Fluent analysis software for the proposed design. Figure 12c and 12d, illustrates the fluid dynamics in the concept design. The flow of air in the water medium is highly recommended in concept one as there is an intermediate valve placed to increase the turbulence pressure artificially. At the same time, the flow direction is strongly generated in concept 1one to improve the airflow outlet velocity. In concept two, the velocity of the air is found less, and the turbulence is not as in concept one. A significant factor is that the relative humidity of the air outlet was found attractive with concept one compared to concept two. Therefore, Concept one has been derived as the best design to substitute a hospital human health safety product.

7. RESEARCH FINDINGS

7.1 Design Optimization of Office Chair Star Base Leg using Product LCM

The implementation of PLCM provides several business benefits as follows. The overall weight of 230 g is reduced from the concept model. Apparently, 230 g of weight reduction/loss is noted comparing to that of the concept model. Product development can be completed more quickly. Design teams can work faster and could accelerate the transfer of design data to production. Utilizing the potential of collaborative designing, opens the opportunity to reduce both material and production costs, as up to 70% of a product's cost is decided through the design stage. Overall Product Time to Market delivery is reduced 20%. For an example, a chair has a lead time (after research phase) of 12months to get released in the market (excluding PLCM).

7.2 Sustainable design and development of cleanser unit

From the investigation, the hair trimmer cleaner is utilized to plan and re-enact to fix the attainability of the item to create and popularized. Following are the focuses to drawn from the recreation and investigation of the cartridge for disturbance stream. On simulation, the pump working pressure induced in the pump is 950 Pa and which is close to the actual system of the pump maximum pressure of 1000 Pa. At the same the maximum fluid discharge at the wash zone is 1.8 g/s of flow to clean the hair trimmer cutting zone. With respect to velocity contour, the maximum velocity of the detergent liquid recorded at the pump is 0.95 m/s. It was found reduced due to turbulence in the wash zone and subsequently increased due to gravity flow. The baffle in the cartridge is designed on counter face of the housing. It has induced the fluid to flow on alternate openings and turbulence found increased. It may support to collect the hard debris over the cartridge and supports to settle. This will help the trimmer to maintain hygienic and safe service on next usage.

7.3 Design and development of air humidifier to support the medical industries

This research and product development through design, analysis, and prototyping is made for the medical industry to support air humidifier systems for pandemic conditions. The investigation shows that the air humidifier developed in this research is a reusable and cost-cutting product to a maximum of 16% from the existing product. In

addition, the developed unit has not compromised the system's efficiency compared to the current unit. The relative humidity of the system outlet has 99% of humidity at a temperature of 37° C. The analysis identified the optimal environmental temperature is 18°C and 37°C as minimum and maximum record temperatures. The proposed unit has been highly recommended for biomedical instrumentation to meet patients' demand for ventilators during the pandemic.

8. ORGANIZATION OF THESIS

CHAPTER 1 – INTRODUCTION: In this chapter, the different human interfacing devices are identified from the current scenario. The human interfaces are identified from the three different such as medical, hospitality and health care devices. From the industrial point of view, the need for the design and modifications in the product are studied in detail. The discussion on the product life cycle assessment, sustainability goals, design, development, reliability of the product are highlighted. The FEA software which helps to enhance the life cycle for the new product development are also discussed in detail.

CHAPTER 2 – LITERATURE REPORT: In this chapter a detailed literature study is made with profound research articles. As the products are very commercial and the articles are very reclusive, some of the industrial standards are in consideration. The recent research on the similar sustainable product development are correlated with the existing commercial product for discussion. The research gap initiated from the detailed literature survey and the objectives were frame. Based on the objectives the proposed research methodologies were developed.

CHAPTER 3 – METHODOLOGY: This explains depicts the tools adopted for product life cycle assessment, product design and evaluation. The recent software (design modules) for product designing is discussed in details. The product evaluation tools like finite element analysis (FEA) for structural and computational fluid dynamics (CFD) analysis are used for product sustainability. The candidate material and experimental process were also discussed in detail for the product validation.

CHAPTER 4 – RESULTS AND DISCUSSION: In this chapter, the outcome of the following products design and development are explained in detail.

4.1 Design Optimization of Office Chair Star Base Leg using Product LCM

4.2 Design and development of commercial system cleanser unit for trimmers

4.3 Design and development of air humidifier to support the medical industries

CHAPTER 5 – CONCLUSIONS: This chapter includes the summary of the aforementioned chapters made after the careful design and analysis of the product. Based on the results and discussion, the conclusions are made for the research work and the future scopes of the work were discussed in this chapter. This chapter concludes the research findings in the aspects of product design and development for implementation.

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List of Publication

1. **Ganesh Raj Kumar**, Adam Khan M, S Rajesh, JT Winowlin Jappes and SP Jani, "A study on design, development, optimization and validation of product development framework for humidifier chamber", *International Journal on Interactive Design and Manufacturing*, (2023).
2. **N. Ganesh Raj kumar**, M. Adam Khan, S. Rajesh and B Shahul Hamid Khan, "Sustainable design and development of commercial system cleanser unit for trimmers", Part E: *Journal of Process Mechanical Engineering*, (2022). [doi.org/10.1177/09544089221085149].
3. **N. Ganesh Raj kumar**, M. Adam Khan, S. Rajesh and Waleed F. Faris (2020) "Design optimization of office chair star base leg using product LCM and anisotropic material properties from injection moulding simulation", *Materials Today: Proceedings* (In Press) https://doi.org/10.1016/j.matpr.2020.03.187